

Superconductivity at 5.4 K in β -Bi₂Pd

Yoshinori Imai^{*1}, Fuyuki Nabeshima¹, Taiki Yoshinaka¹, Kosuke Miyatani¹, Ryusuke Kondo², Seiki Komiya³,
Ichiro Tsukada³, Atsutaka Maeda¹

¹ Department of Basic Science, the University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

² Department of Physics, Okayama University, 3-1-1 Tsushimanaka, kita-ku, Okayama, 700-8530 Japan

³ Central Research Institute of Electric Power Industry, 2-6-1 Nagasaka, Yokosuka, Kanagawa 240-0196, Japan

We investigate bulk superconductivity in a high-quality single crystal of Bi₂Pd (β -Bi₂Pd, space group; $I4/mmm$) with a superconducting transition temperature of 5.4 K by exploring its electrical resistivity, magnetic susceptibility, and specific heat. The temperature dependence of the electrical resistivity shows convex-upward behaviors at temperatures greater than 40-50 K, which can be explained by a parallel-resistor model. In addition, the temperature dependences of the upper critical magnetic field and the specific heat suggest that β -Bi₂Pd is a multiple-band/multiple-gap superconductor.

KEYWORDS: superconductivity, multiple superconducting gaps, β -Bi₂Pd, Pd-Bi alloys, electrical resistivity, parallel-resistor model, upper critical field

Studies of alloy superconductors(SCs) were of considerable interest in the 1950s and 1960s. Matthias established the empirical law that the superconducting transition temperature, T_c , depends on the number of valence electrons; this law is widely known as the Matthias rule.¹ Among Pd-Bi alloys, several superconducting materials, which were summarized in the review paper reported by Matthias *et al.*,¹ have been identified: α -PdBi (monoclinic structure, space group $P2_1$), with a T_c of 3.8 K; α -Bi₂Pd (monoclinic structure, space group $C2/m$), with a T_c of 1.73 K; β -Bi₂Pd (tetragonal structure, space group $I4/mmm$), with a T_c of 4.25 K;² and γ -phase (Pd_{2.5}Bi_{1.5}, hexagonal structure, space group $P63/mmc$), with a T_c of 3.7-4 K.³ Among these alloys, the α -PdBi phase has recently been investigated as a non-centrosymmetric SC.⁴ The results of studies have shown that α -BiPd is a conventional BCS-like SC and that the overall effect of the no-inversion symmetry is of minor importance with respect to the bulk properties in α -BiPd. However, no detailed reports concerning the physical properties of the other Pd-Bi superconducting phases, other than those that have detailed their T_c values and lattice parameters, have been published.

In this Letter, we focus on one of the Pd-Bi alloys, β -Bi₂Pd, the crystal structure of which is shown in Fig. 1(a), and report the results of our investigations of a β -Bi₂Pd single crystal. An early study² reported that this compound showed superconductivity at temperatures less than 4.25 K. However, we found that, by improving the crystal quality, the T_c of β -Bi₂Pd can reach 5.4 K. In addition, the temperature dependences of the upper critical magnetic field and the specific heat suggest that β -Bi₂Pd is a multiple-band/multiple-gap SC. While multigap superconductivity where the gaps on the different part of the Fermi surface become different magnitudes was proposed theoretically,⁵ the first experimental observation of the possible existence of two distinct su-

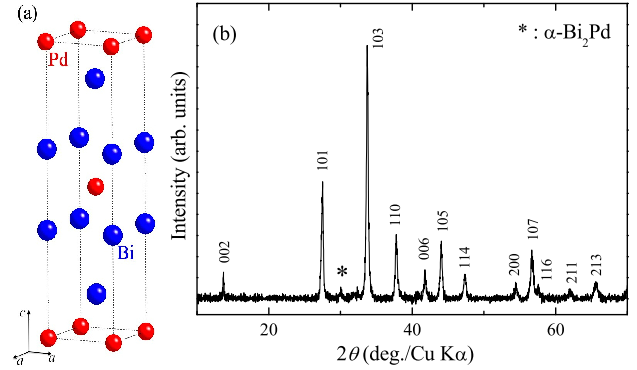


Fig. 1. (color online) (a) Schematic crystal structure of β -Bi₂Pd. (b) Powder X-ray diffraction pattern at room temperature using Cu K α radiation for β -Bi₂Pd single crystal.

perconducting gaps was the tunneling measurement in Nb-doped SrTiO₃.⁶ The existence of multiple superconducting gaps leads to the anomalous temperature dependences in the specific heat, the upper critical magnetic field, the penetration depth, and so on.⁷⁻¹³ After the discovery of the typical multigap SC, MgB₂,^{7,14} numerous studies on multigap superconductivity have been carried out. It is now well known that there are several multigap SCs such as NbSe₂,¹⁵ Lu₂Fe₃Si₅,^{8,11} and the iron-based SCs.^{12,16} One of the interesting aspects in multigap SCs is a variety of pairing mechanisms. In iron-based SCs, the novel s_{\pm} -state where a sign reversal of the gap function occurs between the hole and the electron pockets has been proposed as one of possible scenarios.^{17,18} We demonstrate that β -Bi₂Pd is also a new candidate of a multigap SC from the results of the specific heat and the upper critical magnetic field.

Bi₂Pd single crystals were grown via a melt-growth method. The starting materials were a grain of Bi (5N) and a wire of Pd (3N). These materials, in the prescribed molar ratio of Bi : Pd = 2 : 1 (total: 2 g),

^{*}E-mail address: imai@maeda1.c.u-tokyo.ac.jp

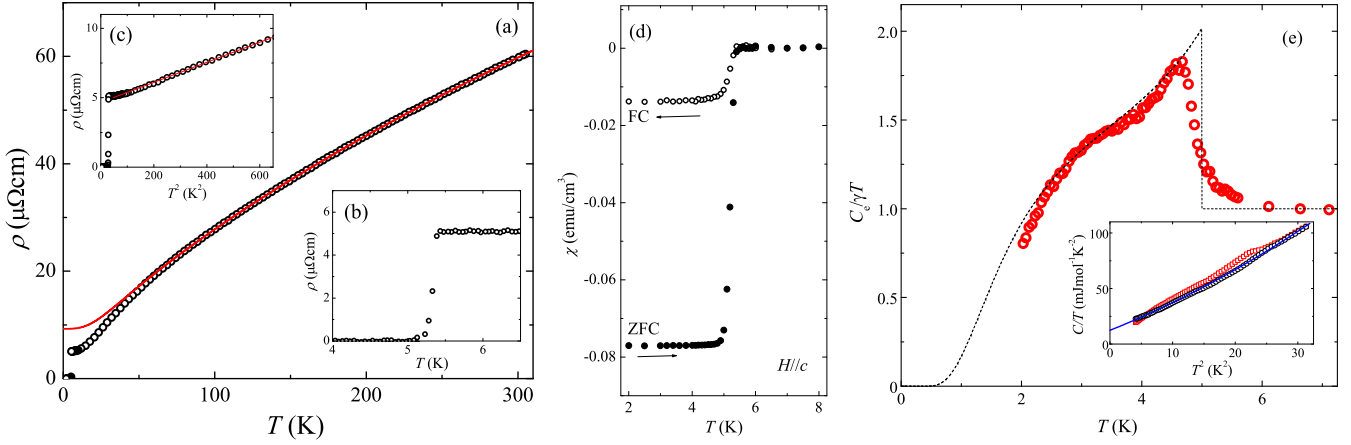


Fig. 2. (color online) (a) Temperature dependence of the electrical resistivity (ρ) of a β -Bi₂Pd single crystal. The inset (b) shows ρ near T_c ; ρ at temperatures less than 25 K is plotted in the inset (c) as a function of T^2 . (d) Temperature dependence of the magnetic susceptibility of a β -Bi₂Pd single crystal measured in a magnetic field of 2 Oe. The closed and open circles represent the measurements in the zero-field cooling (ZFC) and field-cooling (FC) states, respectively. (e) Temperature dependence of normalized electronic specific heat in a zero field. The dashed curve is calculated by using the two-band model ($2\Delta_1/k_B T_c = 2.5$, $2\Delta_2/k_B T_c = 6$, $\gamma_1/\gamma_n = 0.90$) of which details are described in the text. The specific heat divided by temperature at $\mu_0 H = 0$ T (red squares) and 0.6 T (black circles) is plotted in the inset as a function of T^2 . The details of the blue solid curve are described in the text.

were sealed in an evacuated quartz tube. This quartz tube was heated at 900°C for 24 h, successively cooled down to 600°C for 72 h, and then quenched in cold water. All of the products were characterized by powder X-ray diffraction (XRD) using Cu K α radiation at room temperature. Magnetic susceptibility measurements were performed using a superconducting quantum interference device (SQUID) magnetometer. The electrical resistivity, ρ , was measured using the four-terminal method over the temperature range of 0.5 to 300 K under magnetic fields as strong as 3 T. The specific heat was measured using the thermal-relaxation method at temperatures as low as 2 K on a commercial apparatus (Physical Property Measurement System, Quantum Design).

Figure 1(b) shows the XRD pattern of a Bi₂Pd single crystal. Except for a few peaks that resulted from α -Bi₂Pd, all of the peaks were indexed on the basis of a tetragonal lattice (no. 144, $I4/mmm$) with $a = 3.37$ Å and $c = 12.96$ Å. These lattice parameters are in good agreement with those reported previously.^{2,19}

The temperature dependence of ρ for a β -Bi₂Pd single crystal is shown in Fig. 2(a). The large residual resistivity ratio (RRR, $\rho(T = 300 \text{ K})/\rho(T = 6 \text{ K})$) of 12 indicates the high quality of the crystal. The T_c^{onset} , which is defined as the temperature at which ρ begins to deviate from the normal-state behavior, and the T_c^{zero} , which is defined as the temperature at which ρ becomes zero, were estimated to be 5.4 K and 5.3 K, respectively, as shown in Fig. 2(b). These values are greater than the value of 4.25 K that was reported in previous papers.^{2,19} The temperature dependence of the magnetic susceptibility in a magnetic field of 2 Oe is shown in Fig. 2(d). This result reveals that the diamagnetic transition of β -Bi₂Pd occurs at a temperature less than 5.4 K, which is in good agreement with the $\rho(T)$ data. Here, it is interesting to note that T_c of β -Bi₂Pd reported here is almost the same as that of Pd-intercalated Bi₂Te₃,²⁰ where the possibility

that the topological insulator Bi₂Te₃ can be made into a SC by Pd intercalation between the Bi₂Te₃ layers is argued, with a very small superconducting volume fraction ($< 1\%$).

The temperature dependence of ρ for β -Bi₂Pd exhibits the convex-upward characteristics at temperatures greater than 50 K; these characteristics are similar to those observed for A15 SCs.^{21–24} Fisk and Webb have proposed that the resistivity of A15 compounds at high temperatures saturate at a value, ρ_{sat} , that corresponds to the mean free path on the order of the interatomic spacing.²³ Wiesmann *et al.*²⁵ developed this idea proposed by Fisk and Webb and found empirically that the ρ of A15 compounds could be described by a parallel-resistor model:

$$\rho(T) = \left[\frac{1}{\rho_{\text{sat}}} + \frac{1}{\rho_{\text{ideal}}(T)} \right]^{-1}, \quad (1)$$

where ρ_{sat} is a resistivity saturated at high temperatures and is independent of T , and $\rho_{\text{ideal}}(T)$ is the “ideal” contribution according to Matthiessen’s rule, $\rho_{\text{ideal}}(T) = \rho_{\text{ideal},0} + \rho_{\text{ideal},L}(T)$. Here, $\rho_{\text{ideal},0}$ is the ideal temperature-independent residual resistivity caused by the impurity scattering. $\rho_{\text{ideal},L}(T)$ is the temperature-dependent contribution caused by thermally-excited phonons, which can be expressed by the Bloch-Grüneisen formula or by Wilson’s theory.^{26,27}

$$\rho_{\text{ideal},L}(T) = C_1 \left(\frac{T}{\theta_D} \right)^r \int_0^{\frac{\theta_D}{T}} \frac{x^r}{(e^x - 1)(1 - e^{-x})} dx, \quad (2)$$

where C_1 is a numerical constant, θ_D is the Debye temperature, and the values of the exponent r are 3 and 5 for Wilson’s theory and the Bloch-Grüneisen formula, respectively. The data for ρ from 300 K to 75 K were fitted to eq. (1), and the fitted result is shown in Fig. 2(a) as the solid curve. For $\rho_{\text{ideal},L}(T)$, we found that a better fit for

$\rho(T)$ in β -Bi₂Pd is given by Wilson's expression (specifically, $r = 3$ in eq. (2)), which takes into account the interband electron-phonon Umklapp scattering between a low-mass s-band and a heavy-mass d-band.²⁷ The best-fitted result yields the values of 134 K for θ_D , 241 $\mu\Omega\text{cm}$ for ρ_{sat} , 9.63 $\mu\Omega\text{cm}$ for $\rho_{\text{ideal},0}$, and 63.3 $\mu\Omega\text{K}^{-3}$ for C_1 . The value of θ_D is very close to that obtained from the specific heat measurement, as will be discussed later. These results show that the parallel-resistor model explains the $\rho(T)$ behavior of β -Bi₂Pd well at high temperatures. In contrast, notable deviations between the experimental data and the parallel-resistor model are observed at low temperatures. In Fig. 2(c), ρ is plotted as a function of T^2 at low temperatures, which shows that the resistivity is proportional to T^2 at temperatures less than 25 K. A similar crossover from the T^2 behavior to the saturated behavior upon heating has been observed in A15 compounds such as Nb₃Sn^{21,28} and in β -pyrochlore oxides, AO₂O₆ ($A = \text{K, Rb, Cs}$).²⁹ Some mechanisms for the T^2 -dependence of $\rho(T)$ have been proposed.^{30–35} However, the origin of the T^2 -dependence of ρ in β -Bi₂Pd cannot be specified solely from the results in this Letter; further studies are needed.

Next, the specific heat divided by temperature, C/T , at $\mu_0 H = 0$ (red squares), 0.6 T (black circles) is plotted in the inset of Fig. 2(e) as a function of T^2 . C/T at $\mu_0 H = 0.6$ T, where superconductivity is fully suppressed above 2 K, was fitted to the expression

$$C = \gamma_n T + \beta_n T^3 + \alpha_n T^5, \quad (3)$$

where $\gamma_n T$ is the electronic term, C_e , and $\beta_n T^3 + \alpha_n T^5$ represents the phonon contribution. From the fitting by eq.(3), which is shown in the inset of Fig. 2(e) as the blue solid curve, we obtained the parameters $\gamma_n = 12 \text{ mJmol}^{-1}\text{K}^{-2}$, $\beta_n = 2.3 \text{ mJmol}^{-1}\text{K}^{-4}$, $\alpha_n = 0.02 \text{ mJmol}^{-1}\text{K}^{-6}$. The existence of T^5 term in the normal-state specific heat suggests a complex phonon density of states. From this value of β_n , θ_D was estimated to be 136 K using the relation $\theta_D = (12\pi^4 N k_B / 5\beta_n)^{1/3}$,²⁶ where N is the number of atoms, and k_B is the Boltzmann constant. This value of θ_D is similar to that obtained from the analysis of the $\rho(T)$ data using eq. (1), as previously mentioned. The temperature dependence of normalized electronic specific heat at $\mu_0 H = 0$ T, which is estimated by using above parameters, is shown in Fig. 2(e). The clear jump is appeared in $C_e/\gamma T$ at temperature of 5.0 K. This value is slightly smaller than T_c estimated from the temperature dependences of ρ and χ . The magnitude of the jump at $T = T_c$, ΔC , is 40 $\text{mJmol}^{-1}\text{K}^{-1}$, and the value of the normalized specific-heat jump, $\Delta C/\gamma_n T_c$, is 0.82. This value is smaller than that expected in the simple BCS weak-coupling limit, i.e., 1.43. In addition, C_e of β -Bi₂Pd below T_c shows a peculiar temperature dependence. That is, there is a plateau at approximately 3 K. One might think that this plateau results from some impurity phases, for example amorphous Bi or Bi-Pd alloys other than β -Bi₂Pd. However, there is no anomaly in $\chi(T)$ at $T \sim 3$ K. Thus, it is unlikely that the origin of this plateau in the normalized electronic specific heat is an impurity phase. These features, that is, the small

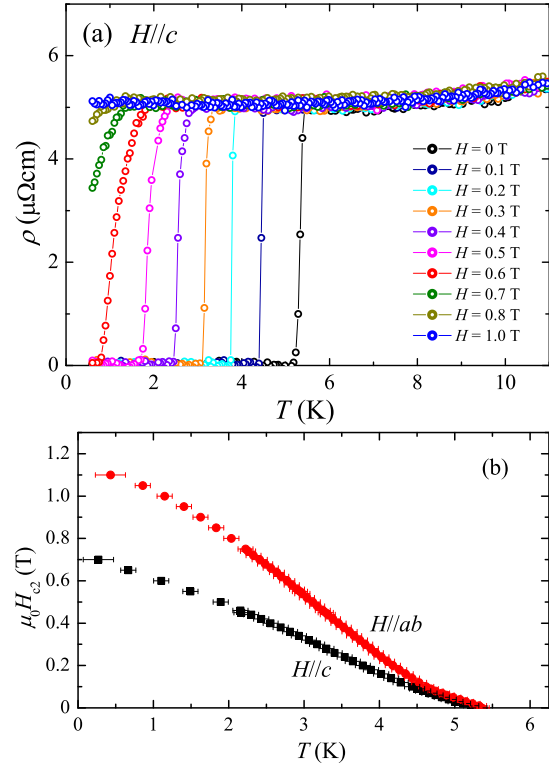


Fig. 3. (color online) (a) Temperature dependence of the electrical resistivity of a β -Bi₂Pd single crystal in a magnetic field parallel to the c -axis. The upper critical field, $\mu_0 H_{c2}$, is plotted in (b) as a function of temperature. The closed circles and squares represent the $\mu_0 H_{c2}(T)$ data for magnetic fields parallel to the ab -plane and to the c -axis, respectively.

jump at T_c and the plateau at approximately 3 K, in $C(T)$ of β -Bi₂Pd are familiar in the multigap SCs.^{7,8,36} In the case of a SC with a single gap, the entropy, S , and C are described as follows,³⁷

$$\frac{S}{\gamma_n T_c} = -\frac{6}{\pi^2 k_B T_c} \int_0^\infty [f \ln f + (1-f) \ln (1-f)] d\epsilon, \quad (4)$$

$$\frac{C}{\gamma_n T_c} = t \frac{d(S/\gamma_n T_c)}{dt}, \quad (5)$$

where $f = [\exp(E/k_B T) + 1]^{-1}$. The energy of quasi-particles is given by $E = [\epsilon^2 + \Delta^2(t)]^{0.5}$, where ϵ is the energy of the normal electrons relative to the Fermi surface and $\Delta(t) = \Delta_0 \delta(t)$ is the temperature dependence of the gap energy. Here, $\delta(t)$ is the normalized BCS gap at the reduced temperature, $t = T/T_c$.³⁸ For the analysis of the data for β -Bi₂Pd, we use the two-band, two-gap model, where the total specific heat is considered as the sum of the contributions of each band calculated independently according to eq.(5), as is the case with MgB₂ and Lu₂Fe₃Si₅.^{7,8} Each band is characterized by the Sommerfeld coefficient, γ_i , with $\gamma_1 + \gamma_2 = \gamma_n$. We calculate the specific heat by this two-gap model using three parameters of two gaps (Δ_1, Δ_2) and the relative weights ($\gamma_1/\gamma_n \equiv x, \gamma_2/\gamma_n \equiv 1-x$), and one of the calculated results is shown as the dashed curve in Fig. 2(e).

The curve calculated by the two-gap model is in agreement with the experimental data at least above 2 K, which suggests that β -Bi₂Pd is a multigap SC. In this analysis, however, there is still some uncertainty and it is difficult to determine only one set of three parameters for lack of the experimental data of C at temperatures less than 2 K. The more detailed analysis requires the data at lower temperatures, and these measurements are currently in progress.

The effect of a magnetic field on ρ is shown in Fig. 3(a). The T_c decreases almost linearly with increasing a magnetic field. The upper critical field, $\mu_0 H_{c2}$, which is defined as the field in which ρ becomes half the value of the normal-state resistance, is plotted in Fig. 3(b) as a function of temperature. The upper critical field extrapolated to $T = 0$ K, namely, $\mu_0 H_{c2}(0)$, is estimated to be 1.13 ± 0.05 T ($H_{c2}^{ab}(0)$) and 0.73 ± 0.05 T ($H_{c2}^c(0)$) for magnetic fields parallel and perpendicular to the ab -plane, respectively. These results give Ginzburg-Landau coherence lengths of $\xi_{ab}(0) \sim 212 \pm 8$ Å and $\xi_c(0) \sim 137 \pm 2$ Å, using $\mu_0 H_{c2}^{ab}(0) = \Phi_0 / 2\pi \xi_{ab}(0) \xi_c(0)$ and $H_{c2}^c(0) = \Phi_0 / 2\pi \xi_{ab}(0)^2$, where $\Phi_0 = 2\pi\hbar/2e = 2.07 \times 10^{-15}$ Tm² is the magnetic flux quantum. The anisotropy parameter, Γ , which is defined as $\Gamma = H_{c2}^{ab}(0)/H_{c2}^c(0)$, is found to be 1.6. It should be noted that the temperature dependence of $\mu_0 H_{c2}$ in β -Bi₂Pd reveals a positive curvature close to T_c , which becomes negative at temperatures less than approximately 3 K, as shown in Fig. 3(b). These temperature dependences have also appeared in other multigap SCs, such as MgB₂,^{10,39} LaFeAs(O,F),^{12,40} and SrPtAs.⁴¹ In addition, some theoretical papers have explained this temperature dependence of $\mu_0 H_{c2}$ on the basis of multiple superconducting gaps.^{42–44} This result for $\mu_0 H_{c2}$, together with the $C_e(T)$ data, suggests that β -Bi₂Pd is a SC with multiple superconducting gaps. Indeed, the presence of different Fermi surfaces has already been predicted by a band calculation.⁴⁵ Thus, our experimental findings suggest that the superconducting gaps open on the different Fermi surfaces with different magnitudes.

In conclusion, we observed bulk superconductivity with a T_c of 5.4 K in β -Bi₂Pd by investigating the electrical resistivity, the magnetic susceptibility, and the specific heat. The value of T_c reported in this Letter is higher by approximately 1.2 K than those reported in previous papers and is the highest among the Pd-Bi alloy systems. In addition, the temperature dependences of the upper critical field and the specific heat suggest that β -Bi₂Pd is a multigap superconductor.

This work was performed using facilities of the Cryogenic Research Center, the University of Tokyo, and was supported by a MEXT/JSPS Grant-in-Aid for Scientific Research (Grant Number 43244070).

- 1) B. T. Matthias, T. H. Geballe, and V. B. Compton: *Rev. Mod. Phys.* **35** (1963) 1.
- 2) N. N. Zhuravlev: *Zh. Eksp. Teor. Fiz.* **32** (1957) 1305.
- 3) N. N. Zhuravlev: *Sov. Phys. Crystallogr.* **3** (1958) 506.
- 4) B. Joshi, A. Thamizhavel, and S. Ramakrishnan: *Phys. Rev. B* **84** (2011) 064518.
- 5) H. Suhl, B. T. Matthias, and L. R. Walker: *Phys. Rev. Lett.* **3** (1959) 552.
- 6) G. Binnig, A. Baratoff, H. E. Hoenig, and J. G. Bednorz: *Phys. Rev. Lett.* **45** (1980) 1352.
- 7) F. Bouquet, Y. Wang, R. A. Fisher, D. G. Hinks, J. D. Jorgensen, A. Junod, and N. E. Phillips: *Europhys. Lett.* **56** (2001) 856.
- 8) Y. Nakajima, T. Nakagawa, T. Tamegai, and H. Harima: *Phys. Rev. Lett.* **100** (2008) 157001.
- 9) X. X. Xi: *Rep. Prog. Phys.* **71** (2008) 116501.
- 10) L. Lyard, P. Samuely, P. Szabo, T. Klein, C. Marcenat, L. Paulius, K. H. P. Kim, C. U. Jung, H.-S. Lee, B. Kang, S. Choi, S.-I. Lee, J. Marcus, S. Blanchard, A. G. M. Jansen, U. Welp, G. Karapetrov, and W. K. Kwok: *Phys. Rev. B* **66** (2002) 180502.
- 11) R. T. Gordon, M. D. Vannette, C. Martin, Y. Nakajima, T. Tamegai, and R. Prozorov: *Phys. Rev. B* **78** (2008) 024514.
- 12) G. R. Stewart: *Rev. Mod. Phys.* **83** (2011) 1589.
- 13) Y. Imai, H. Takahashi, K. Kitagawa, K. Matsubayashi, N. Nakai, Y. Nagai, Y. Uwatoko, M. Machida, and A. Maeda: *Journal of the Physical Society of Japan* **80** (2011) 013704.
- 14) J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu: *Nature* **410** (2001) 63.
- 15) E. Boaknin, M. A. Tanatar, J. Paglione, D. Hawthorn, F. Ronning, R. W. Hill, M. Sutherland, L. Taillefer, J. Sonier, S. M. Hayden, and J. W. Brill: *Phys. Rev. Lett.* **90** (2003) 117003.
- 16) Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono: *Journal of the American Chemical Society* **130** (2008) 3296.
- 17) I. I. Mazin, D. J. Singh, M. D. Johannes, and M. H. Du: *Phys. Rev. Lett.* **101** (2008) 057003.
- 18) K. Kuroki, S. Onari, R. Arita, H. Usui, Y. Tanaka, H. Kontani, and H. Aoki: *Phys. Rev. Lett.* **101** (2008) 087004.
- 19) N. E. Alekseevski, N. N. Zhuravlev, and I. I. Lifanov: *Zh. Eksp. Teor. Fiz.* **27** (1954) 125.
- 20) Y. S. Hor, J. G. Checkelsky, D. Qu, N. P. Ong, and R. J. Cava: *J. Phys. Chem. Sol.* **72** (2011) 572.
- 21) D. W. Woodard and G. D. Cody: *Phys. Rev.* **136** (1964) A166.
- 22) M. Milewits, S. J. Williamson, and H. Taub: *Phys. Rev. B* **13** (1976) 5199.
- 23) Z. Fisk and G. W. Webb: *Phys. Rev. Lett.* **36** (1976) 1084.
- 24) O. Gunnarsson, M. Calandra, and J. E. Han: *Rev. Mod. Phys.* **75** (2003) 1085.
- 25) H. Wiesmann, M. Gurvitch, H. Lutz, A. Ghosh, B. Schwarz, M. Strongin, P. B. Allen, and J. W. Halley: *Phys. Rev. Lett.* **38** (1977) 782.
- 26) J. M. Ziman: *Principles of the Theory of Solids 2nd ed.* (Cambridge).
- 27) A. H. Wilson: *Proc. R. Soc. Lond. A* **167** (1938) 580.
- 28) G. W. Webb, Z. Fisk, J. J. Engelhardt, and S. D. Bader: *Phys. Rev. B* **15** (1977) 2624.
- 29) Z. Hiroi, J. Yamaura, and K. Hattori: *J. Phys. Soc. Jpn.* **81** (2012) 011012.
- 30) P. L. Taylor: *Phys. Rev.* **135** (1964) A1333.
- 31) M. Gurvitch: *Phys. Rev. Lett.* **56** (1986) 647.
- 32) M. Reizer and A. Sergeev: *Zh. Eksp. Teor. Fiz.* **92** (1987) 2291.
- 33) N. G. Ptitsina, G. M. Chulkova, K. S. Il'in, A. V. Sergeev, F. S. Pochinkov, E. M. Gershenson, and M. E. Gershenson: *Phys. Rev. B* **56** (1997) 10089.
- 34) M. Kaveh and N. Wiser: *Adv. Phys.* **33** (1984) 257.
- 35) T. Dahm and K. Ueda: *Phys. Rev. Lett.* **99** (2007) 187003.
- 36) Y. Wang, T. Plackowski, and A. Junod: *Physica C* **355** (2001) 179.
- 37) H. Padamsee, J. E. Neighbor, and C. A. Shiffman: *J. Low Temp. Phys.* **12** (1973) 387.
- 38) B. Mühlischlegel: *Z. Phys.* **155** (1959) 313.
- 39) A. Gurevich: *Physica C* **456** (2007) 160.
- 40) F. Hunte, J. Jaroszynski, A. Gurevich, D. C. Larbalestier, R. Jin, A. S. Sefat, M. A. McGuire, B. C. Sales, D. K. Christen, and D. Mandrus: *Nature* **453** (2008) 903.
- 41) Y. Nishikubo, K. Kudo, and M. Nohara: *J. Phys. Soc. Jpn.* **80** (2011) 055002.
- 42) A. Gurevich: *Phys. Rev. B* **67** (2003) 184515.

-
- 43) M. E. Zhitomirsky and V.-H. Dao: Phys. Rev. B **69** (2004) 054508.
- 44) V. Kogan and R. Prozorov: arXiv:1112.0996.
- 45) R. Xu, R. A. de Groot, and W. van der Lugt: J. Phys.: Condens. Matter **4** (1992) 2389.